

## Photoinduced effects in optical waveguides

E.M. Dianov, P.G. Kazansky, D. Yu. Stepanov

General Physics Institute of USSR Academy of Sciences,  
Department of Fiber Optics, 38 Vavilov Street, Moscow, USSR

### ABSTRACT

Photoinduced effects in optical waveguides are compared: photoinduced conversion of radiation polarization in lithium niobate optical waveguides and photoinduced second harmonic generation in glass optical fibers. The cause of both phenomena consists in unusual interference between radiation with orthogonal polarization in one case and between radiation with different frequency in the other one.

### 1. INTRODUCTION

It is known that the second order optical nonlinearity is forbidden in amorphous medium, such as glass materials, because of inversion symmetry. Therefore, the investigation of efficient second harmonic generation (SHG) in fused silica fibers is of great interest.<sup>1</sup>

Different models of the appearance of second-order susceptibility grating in silica fibers have been proposed.<sup>2-10</sup> However, for the time being none of the models have been confirmed completely.<sup>11-13</sup>

It is interesting to note that there is an effect similar to photoinduced SHG - photoinduced light polarization conversion in lithium niobate optical waveguides.<sup>14-17</sup> Such conversion is attributed to circular photovoltaic effect (PVE),<sup>18-20</sup> being the special case of bulk photovoltaic effect.<sup>21</sup> The latter consists in the appearance of a dc current through a homogeneous crystal without a symmetry center under uniform illumination and is the result of an asymmetry of elementary photoelectron processes, e.g. photoionization, in a medium without a symmetry center.<sup>22</sup> The mechanisms of photocurrents induced by linearly and circularly polarized radiation are different and therefore linear and circular photocurrents are discerned.<sup>22</sup> The circular photovoltaic effect consists in conversion of photon angular momentum to charge carrier momentum.<sup>18,19</sup> This effect has not been sufficiently studied for most crystals without symmetry center, because the related circular photocurrent is difficult to measure directly due to its spatial oscillations with a short period, determined by birefringence.<sup>18,23,24</sup>

Formal analogy of the effects of photoinduced light polarization conversion and photoinduced SHG was greatly conducive to proposal of photovoltaic model of the latter.<sup>7</sup> This model is based on coherent photovoltaic effect due to photoionization - the appearance of dc current through a homogeneous medium under uniform illumination by pump and second harmonic and is a result of asymmetry of photoionization by pump and second harmonic.<sup>6,25</sup> Unlike bulk photovoltaic effect this effect is possible in medium with inversion symmetry and only for coherent radiation, the latter is emphasized in the name of the effect.

The appearance of free carriers current in semiconductors and metals under illumination by pump and second harmonic was considered.<sup>16,27</sup> The idea of current arising due to photoionization by pump and second harmonic has been proposed.<sup>6,25</sup> It has been also suggested that this effect can explain

photoinduced SHG in optical fibers.<sup>6</sup> Two contributions to photocurrent have been considered,<sup>25</sup> one of them has been determined by interference between two-photon pump ionization and one-photon second harmonic ionization. It has been suggested that interference between two-photon pump ionization and one-photon second harmonic ionization connected with photoinduced SHG.<sup>28,29</sup> Analogous idea was suggested.<sup>30</sup> Asymmetry of such ionization due to photoemissive effect has been investigated.<sup>31</sup>

In the present paper photoinduced effects are considered in consecutive order to show their analogy which in our opinion, will help to construct the model of photoinduced SHG.

## 2. PHOTOINDUCED LIGHT POLARIZATION CONVERSION IN LITHIUM NIOBATE WAVEGUIDES

### 2.1. Experimental findings

Experimental waveguides were fabricated by titanium thermodiffusion into Y and Z-cut LiNbO<sub>3</sub> crystals from Ti strips of 10 μm width, 300Å thickness and 15mm length deposited along the X-axis. Two series of waveguides were fabricated, one with diffusion taking place in air and the other in humid oxygen. In both cases the process was carried out at 960C for six hours. The emission of a He-Ne laser (λ=630 nm) with polarization corresponding to ordinary mode excitation was injected into the polished butt end of the waveguide using a micro-lens as illustrated in Fig. 1. Fig. 2 shows the time dependence of the ordinary and extraordinary modes and the total power carried in a Y-cut channel waveguide. Initially only E<sup>Y</sup><sub>mn</sub> (TM) modes propagate in the waveguide, carrying a power of P=50μW; subsequently they are converted into E<sup>Z</sup><sub>mn</sub> (TE) modes of twice lower power in the stationary state. Reduction of total light power with time till some stationary state was apparently due to photoinduced light scattering. No polarization conversion was observed when E<sup>Z</sup><sub>mn</sub> modes were excited in the channel waveguide, these modes corresponding to extraordinary waves in Y-cut LiNbO<sub>3</sub>. A similar effect was observed in Z-cut channel waveguides, the only difference consisting in that in this case E<sup>Y</sup><sub>mn</sub> (TE) modes, corresponding to an ordinary wave, were converted into E<sup>Z</sup><sub>mn</sub>(TM) modes, corresponding to an extraordinary wave in Z-cut LiNbO<sub>3</sub>, at increased power level of the exciting light. Thus, in Y and Z-cut channel waveguides the appearance of modes with a polarization corresponding to that of an extraordinary wave was observed.<sup>14</sup>

Fig. 3 shows the power of the extraordinarily polarized mode P<sub>e</sub>, as a function of the total light power in the waveguide P, for waveguides fabricated under different conditions. Extraordinary waveguide mode generation can be seen to set in at total light intensities in the waveguide exceeding a threshold value. The presence of the extraordinary mode at power levels below this threshold is mainly due to misalignment of the input polarization relative to the crystal's Y axis. The threshold light intensity (I=P/S, S≅3 · 10<sup>-7</sup>cm<sup>2</sup>) for waveguides fabricated in air constitutes about 2 W/cm<sup>2</sup>. What concerns waveguides fabricated in humid oxygen, their threshold intensity was about 60 times higher and was close to threshold value (about 100 W/cm<sup>2</sup>), measured.<sup>32</sup> Such a high threshold of photoinduced polarization conversion being in agreement with the known effect of higher resistance to optical damage in waveguides fabricated in a humid medium.

## 2.2. Photovoltaic model of photoinduced light polarization conversion

Consider interaction between two orthogonally polarized modes in a Ti:LiNbO<sub>3</sub> channel waveguide propagating along the X-axis (Fig. 1). At the initial stage of interaction the bulk photovoltaic effect (as a result of photoionization of color centers, for example, Fe<sup>2+</sup>) will produce a photocurrent along the Y axis, with a current density<sup>22</sup>:

$$j_Y = i\beta^a \{E_0 E_e \exp[ik(n_0^* - n_e^*)x] - E_0 E_e \exp[-ik(n_0^* - n_e^*)x]\} + \beta_{15}^S \{E_0 E_e \exp[ik(n_0^* - n_e^*)x] + E_0 E_e \exp[-ik(n_0^* - n_e^*)x]\} \quad (1)$$

where  $E_0$  and  $E_e$  are the amplitudes of the interacting waves,  $\beta^a$  is the circular photovoltaic tensor component,  $\beta_{15}^S$  is the linear photovoltaic tensor component,  $k=2\pi/\lambda$ ,  $\lambda$  is the wavelength,  $n_0^*$  and  $n_e^*$  are the effective refractive indices of the ordinary and extraordinary modes, respectively. This photocurrent causes charge separation and leads to an electrostatic field  $\mathcal{E}_Y \approx \sigma^{-1} j_Y$ , being set up ( $\sigma$  is the crystal's photoconductivity). Due to the electro-optic effect, this field varies the crystal's permittivity  $\Delta\epsilon_{ij} = \chi_{ijY} \mathcal{E}_Y$  (where  $\chi_{ijY}$  is the tensor of the second-order nonlinear susceptibility). Since the photocurrent spatially oscillates<sup>23</sup> with a period determined by birefringence  $\Lambda = \lambda/(n_0^* - n_e^*)$ , a spatial phase grating is recorded, that automatically meets the condition of phase matching between the orthogonally polarized modes:  $\vec{K} = \vec{k}_0 - \vec{k}_e$ ,  $|\vec{K}| = 2\pi/\Lambda$ . The grating component shifted by a quarter of the period relative to the polarization oscillation pattern ( $\Delta\epsilon \propto \beta^a \sin[k(n_0^* - n_e^*)x]$ ) causes unidirectional energy exchange between the interacting waves.<sup>33</sup> The unshifted component of the grating determined by the linear photovoltaic effect ( $\Delta\epsilon \propto \beta_{15}^S \cos[k(n_0^* - n_e^*)x]$ ) does not lead to stationary energy exchange and only affects the pattern of stationary state establishment.<sup>33</sup> It can be shown, that photoinduced conversion of radiation polarization is describable by a system of truncated equations:<sup>34,35</sup>

$$\begin{aligned} \frac{dE_e}{dx} &= -\frac{\omega\beta^a}{2\sigma c n_e^*} \chi_{ZY} E_e E_0^2 - \alpha_e E_e \\ \frac{dE_0}{dx} &= -\frac{\omega\beta^a}{2\sigma c n_0^*} \chi_{YZ} E_0 E_e^2 - \alpha_o E_0 \end{aligned} \quad (2)$$

where  $\chi_{ZY} = \chi_{YZ} = \epsilon_e \epsilon_0 r_{51}$  is the electro-optic tensor component,  $c$  and  $\omega$  are the speed and frequency of light,  $\epsilon_e = n_e^2$ ,  $\epsilon_0 = n_0^2$ , and  $\alpha_0$  and  $\alpha_e$  are the damping factors for the ordinary and extraordinary waveguide modes, respectively. The mode overlap integral is assumed to be unity, this being valid with adequate accuracy due to the discussion dealing with the interaction between lower modes, far from cutoff. Proceeding to equations describing intensity,  $I_{e,0} = c n_{e,0}^2 E_{e,0}^2 / 8\pi$ ,  $n = n_e^* = n_0^*$ , and solving the corresponding set of equations for the case of negligible losses, we arrive at:<sup>34</sup>

$$\frac{I_e(x)}{I_o(x)} = \frac{I_e(0)}{I_o(0)} \exp(Gx) \quad (3)$$

where  $I = I_e + I_o$  is total intensity of the radiation in the waveguide and  $G = 8\pi\omega\beta^a n^2 c^2 \sigma^{-1} r_{51} I$  is the gain factor. Thus, two typical features of wave interaction due to circular photovoltaic effect should be

stressed:<sup>33</sup> 1. the periodic structure is recorded by orthogonally polarized waves; 2. energy exchange is unidirectional, with the direction of energy transfer being determined by the sign of the circular photovoltaic tensor component  $\beta^a$ .

From the system of equations (1) it follows that energy will be transferred from the ordinary waveguide mode to the extraordinary mode if the following threshold condition is satisfied:

$$\frac{\omega \beta^a \chi}{2\sigma cn} E_{thr} > \alpha, \quad I > I_{thr} = \frac{cn}{8\pi} E_{thr}^2 - \frac{\lambda}{2\pi n^3 r} \frac{\sigma \alpha_I}{\beta_I^a} \quad (4)$$

where  $\alpha_I = 2\alpha_o \approx 2\alpha_e$ ,  $n - n_o^* \approx n_e^*$ ,  $\beta^a = \frac{8\pi}{cn} \beta$ . In other words, radiation polarization conversion

takes place at light intensities above a certain threshold value,  $I_{thr}$ , in the waveguide, when photoinduced amplification of the extraordinary mode exceeds light losses due to absorption and scattering. Thus, waveguides fabricated in air ( $\sigma \approx 10^{-13} \text{ Ohm}^{-1} \text{ cm}^{-1}$ ,  $\beta_I^a \approx 5 \cdot 10^{-12} \text{ A/W}$ ,  $\alpha \approx 1.5 \text{ dB/cm}$ ,  $\lambda = 630 \text{ nm}$ ) can be shown to feature a threshold radiation intensity of about  $1.8 \text{ W/cm}^2$ .

### 2.3. Effect of applied field on photoinduced light polarization conversion

Photorefractive significantly impairs the performance quality of integrated optics modulators, reducing the modulation depth and increasing light losses. Field of sufficient amplitude applied (compared with photovoltaic field) can make the phase grating disappear.<sup>15</sup> We shall discuss the effects of photoinduced conversion of the radiation polarization in the active modulator zone on the performance of a phase modulator, in case when applied field ( $10^4 \text{ V/cm}$ ) is smaller than photovoltaic field ( $10^5 \text{ V/cm}$ ).

A voltage applied to the electrodes positioned at both sides of a Y-cut  $\text{LiNbO}_3$  waveguide will cause amplitude modulation along with the useful modulation. Variation of the radiation intensity should be a result of the violation of phase synchronism between the TE and TM modes and, consequently, variation of the degree of polarization conversion. The drive voltage  $U$  may be estimated from the equation:  $UL = \lambda d / n^3 r \Gamma$  (where  $\Gamma$  is the overlap integral,  $L$  is the electrode length and  $d$  is the gap between electrodes); at  $\lambda = 0.63 \mu\text{m}$ ,  $L = 10 \text{ mm}$ ,  $d = 10 \mu\text{m}$  and  $\Gamma = 0.3$  the drive voltage will be about 7 volts. Such amplitude modulation was observed in our experiments.<sup>34</sup>

An electrode structure in the form of two parallel aluminum strips  $15 \mu\text{m}$  wide and  $14 \text{ mm}$  long was photolithographically deposited on the crystal to both sides of the waveguides; the gap between electrodes was  $10 \mu\text{m}$ . The voltage was applied after photoinduced light polarization had happened. Then the power of ordinary wave increased and the power of extraordinary wave decreased (Fig. 4). The detected amplitude modulation is a spurious effect from the viewpoint of phase modulator performance. However, electro-optic control for photoinduced conversion of radiation polarization can be treated as a confirmation of the mechanism being based on matching the phases of ordinary and extraordinary modes by means of a phase grating, and may also be used to modulate light by controlling photoinduced polarization conversion in channel waveguides.

### 3. DIRECT OBSERVATION OF CIRCULAR PHOTOCURRENT IN LITHIUM NIOBATE

Photoinduced conversion of light polarization gave indirect evidence in favor of existence of circular photocurrent in lithium niobate. However it was interesting to observe this current directly. Spatially oscillatory photocurrents can be observed by using electrodes on a surface of crystal which is perpendicular to the light propagation direction (Fig. 5a). When the entire volume between the short-circuited electrodes is illuminated uniformly, a photocurrent determined by a thin surface layer of the crystal of thickness  $h \ll \Lambda$  will flow.<sup>24</sup> It can be shown, for example, from equivalent circuit (Fig. 5b), that the small gap between electrode  $d$  is needed in order to increase the full current  $I$  at given power  $P$  (in order to diminish the influence the space oscillations of photocurrent)  $d \ll \Lambda$ :

$$I \sim \beta \frac{Ph}{d} \frac{\Lambda}{d + \Lambda} \quad (5)$$

Circular photocurrent was observed in lithium niobate by this method.<sup>24</sup>

A pair of aluminum electrodes separated by a  $10\mu\text{m}$  gap was applied to polished Y-cut surface of lithium niobate by a photolithographic method. These electrodes were used to measure the photocurrent  $j_x$  which flows in the direction parallel to the X-axis. The beam from an argon laser ( $\lambda = 0.4765\mu\text{m}$ ) with a power of about 13mW was focused on the gap by an 8x objective. The degree of circular polarization of the light was varied by a volume electro-optic modulator. When no voltage was applied to the modulator the light had a linear polarization making an angle of  $45^\circ$  with the optic axes of the modulator and the crystal. The photovoltaic current was measured by an electrometer. Fig. 6 shows the resulting dependence of the current on the phase shift between the field components of the light along X and Z axes ( $E_x$  and  $E_z$ ). Extreme values of the photocurrent at phase shifts  $\pi/2$  and  $3\pi/2$  in the circularly polarized light can be seen. It also follows from this dependence that the maximum linear photocurrent which flows in the crystal at phase shift of  $0, \pi$  and  $2\pi$  is at least an order of magnitude lower than the maximum circular photocurrent ( $\beta^{as} \gg \beta_{15}^s$ ).

### 4. PHOTOVOLTAIC MODEL OF PHOTOINDUCED SECOND HARMONIC GENERATION IN OPTICAL FIBERS

#### 4.1. Photovoltaic mechanism of second-order susceptibility grating appearance in silica fibers

It is known that color centers (such as Ge(N) for example) exist in small quantities in the fiber (primary centers).<sup>3,36</sup> In addition, during the  $\chi^{(2)}$  recording other centers are created (secondary centers). These centers (both primary and secondary) can serve as a source of photoelectrons as a result of interference between two-photon ionization by pump and one-photon ionization by second harmonic.<sup>28, 29</sup> The asymmetry of such photoionization results in the space oscillating coherent photocurrent with the current density given by:

$$j = \beta E_0^2(\omega) E(2\omega) \exp[-i(\Delta kz - \psi)] + c.c. \quad (6)$$

where  $\beta$  is the component of the coherent photovoltaic effect tensor,  $E_0(\omega)$  and  $E(2\omega)$  are amplitudes

of the pump and the second harmonic electric fields,  $\Delta k = k_{2\omega} - 2k_{\omega} = 2\pi/\Lambda$ ,  $\Lambda = (\lambda/2)/(n_{2\omega} - n_{\omega})$  is the period of space oscillations,  $\lambda$  is the pump wavelength,  $n_{\omega}$  and  $n_{2\omega}$  are the effective indices of the pump and the second harmonic waves,  $\psi$  is the constant phase shift, determined by microscopic model of photocurrent, properties of the medium and parameters of radiation. The magnitude of  $\beta$  is dependent on the wavelength  $\lambda$  and the concentration of photovoltaic centers (color centers).

As a result of charge separation and their trapping (in the low-intensity region where the rate of photoelectron generation is low) there will be a strong ( $10^4 - 10^5$  V/cm) electrostatic field<sup>6,7</sup>  $\mathcal{E} = -j/\sigma$  where  $\sigma$  is the photoconductivity which is dependent on wavelength  $\lambda$  and on the defects' concentration. This field will in turn lead to the appearance of a second order susceptibility grating:<sup>6,7</sup>

$$\chi^{(2)} - \chi^{(3)}\mathcal{E} - \beta/\sigma\chi^{(3)}E_0^2(\omega)E(2\omega)\exp[-i(\Delta kz - \psi)] + c.c. \quad (7)$$

where  $\chi^{(3)} \approx 10^{-22}(\text{m/V})^2$  is the third-order susceptibility.

Therefore photovoltaic mechanism of second-order susceptibility grating appearance in silica fibers serves to explain a high enough amplitude of this grating as well as the phase matching of second harmonic generation. Nevertheless one must also explain the efficient amplification of weak seeding radiation.

#### 4.2. Mechanism of photoinduced amplification of second harmonic in optical fibers

As known, second harmonic generation is described by the equation below:<sup>37, 38</sup>

$$\frac{\partial E(2\omega)}{\partial z} = -i \frac{4\pi\omega}{n(2\omega)c} E_0^2(\omega) \chi^{(2)} \exp(i\Delta kz) - \frac{\alpha}{2} E(2\omega) \quad (8)$$

where  $\alpha$  - losses.

It is necessary to add the equation for  $\chi^{(2)}$ . We consider that  $\chi^{(2)}$  appears under the action of electrostatic field  $\mathcal{E}$  caused by coherent photocurrent. Then, from the continuity equation  $\partial\rho/\partial t = -\text{div}(j + \sigma\mathcal{E})$  and  $\chi^{(2)} = \chi^{(3)}\mathcal{E}$  it follows:

$$\frac{\partial \chi^{(2)}}{\partial t} = -\frac{4\pi\chi^{(3)}}{\epsilon} j - \frac{\chi^{(2)}}{\tau} \quad (9)$$

where  $\tau = \epsilon/4\pi\sigma$ ,  $\epsilon$  is a permittivity. Neglecting nonresonance terms and converting to equations for real amplitudes and phases  $(E(2\omega) = \sqrt{8\pi/(n(2\omega)c)} \sqrt{I} \exp(i\varphi)$ ,  $\chi^{(2)} = \chi \exp[i(\Phi - \Delta kz)]$ , where  $I$  is an intensity), we obtain the following set of equations:<sup>37, 38</sup>

$$\frac{\partial I}{\partial z} = \gamma \chi \sqrt{I} \sin(\Phi - \varphi) - \alpha I \quad (10)$$

$$\frac{\partial \Phi}{\partial z} = -\frac{\gamma}{2} \chi \frac{1}{\sqrt{I}} \cos(\Phi - \varphi) \quad (11)$$

$$\frac{\partial \chi}{\partial t} = \delta \sqrt{I} \cos(\varphi - \Phi + \psi) - \frac{\chi}{\tau} \quad (12)$$

$$\frac{\partial \Phi}{\partial t} = \frac{\delta}{\chi} \sqrt{I} \sin(\varphi - \Phi + \psi) \quad (13)$$

where  $\gamma = A \omega I_0(\omega)$ ,  $\delta = -A \frac{4\pi\chi^{(3)}}{\varepsilon} \beta I_0(\omega)$ ,  $A^{-2} = (8\pi/c)^{-3} n^2(\omega) n(2\omega)$ .

The obtained equations are analogous to equations describing the dynamic self diffraction of light beams.<sup>39</sup> It follows from these equations, that the second harmonic intensity increases with fiber length increase under the condition  $\Phi - \varphi > 0$ , i.e. at the presence of the shift of the grating relative to "interference" pattern ( $E^2_0(\omega)E(2\omega)\exp(-i\Delta kz) + c.c.$ ) and fulfillment of the threshold condition:

$$\frac{\gamma \chi}{\sqrt{I(2\omega)}} \sin(\Phi - \varphi) \geq \alpha \quad (14)$$

It is also evident from equations (10) - (13), that the second harmonic amplification in the stationary state ( $\partial\chi/\partial t = 0, \partial\Phi/\partial t = 0$ ) is possible only at nonlocal response of medium ( $\psi \neq 0, \pm \pi$ ). It has been experimentally shown, that  $\psi \approx 0, \pm \pi$  in optical fibers.<sup>40</sup> Recent experiments have shown that  $\psi \approx 0$ .<sup>41,42</sup> Therefore let us consider in more detail the case of local ( $\psi = 0$ ) response of the medium. Then in the stationary state the amplification of second harmonic intensity does not occur:

$I(2\omega) \approx I_0(2\omega)$  (at  $\alpha = 0$ ),  $\chi = \delta \tau \sqrt{I_0(2\omega)}$ , where  $I_0(2\omega)$  is the seed radiation intensity. However, in the nonstationary state ( $\partial\Phi/\partial t \neq 0$ ) the amplification is possible. It can be expressed physically in the following way. While recording the grating moves along the fiber following the movement of "interference" pattern with some delay due to inertia of erasure. Second harmonic generation in the phase with seeding harmonic occurs on the shifted component of the grating and they strengthen each other.

Under the condition of constancy of  $\beta$  and  $\sigma$  the solution of equations (10)-(13) for second harmonic intensity and phase is as follows:

$$I(z, t) = I_0(2\omega) \exp(-2t/\tau - \alpha z) |J_0(2\sqrt{i\kappa t G(z)})|^2 \quad (15)$$

$$\varphi(z, t) = \arg(J_0(2\sqrt{i\kappa t G(z)})) \quad (16)$$

Where  $J_0$  – Bessel's function,  $\kappa = \frac{\gamma\delta}{2}$ ,  $G(z) = \int_0^z g_1^4(z/L_w) dz$ ,  $g_1$  – the normalized form of pump pulse ( $g_1 = \exp[-(z/L_w)^2]$  for Gaussian pulse),  $L_w$  – walk-off distance between the fundamental and the second harmonic pulses.

Then the threshold condition (14) can be approximately written in the following form:

$$\sqrt{2|\kappa|tG(z)} - t/\tau - \alpha z/2 - f(z, t) \geq 0 \quad (17)$$

and the threshold pump intensity can be found:

$$I_0^2(\omega) \geq 2A^{-2} \omega^{-1} \alpha \sigma / (|\beta| \chi^{(3)}) \quad (18)$$

Let us make a numerical evaluation:  $I_0(\omega) \cong 10^9$  W/cm<sup>2</sup> at  $\alpha = 10^{-3}$  cm<sup>-1</sup>,  $\beta/\sigma = 10^{-17}$  m<sup>2</sup>/V<sup>2</sup>.

Therefore, the exponential increase of the second harmonic intensity on fiber length, restricted by walk-off distance occurs. However, from equations (15) and (16) it is impossible to explain different forms of length dependencies of second harmonic intensity at different values of seeding radiation intensity.<sup>43</sup> Therefore, for more accurate description of the phenomenon let us take into account the dependence of conductivity on second harmonic and pump intensities.<sup>38</sup>

$$\sigma = \sigma_0 + \sigma'_\omega I_\omega + \sigma''_\omega I_\omega^2 + \sigma'_{2\omega} I_{2\omega} + \sigma''_{2\omega} I_{2\omega}^2 \quad (19)$$

where  $\sigma_0$  dark conductivity,  $\sigma'_\omega$  and  $\sigma''_\omega$  coefficients of conductivity at one-photon and two-photon absorption of pump radiation, correspondingly,  $\sigma'_{2\omega}$  and  $\sigma''_{2\omega}$  coefficients of conductivity at one-photon and two-photon absorption of second harmonic radiation, correspondingly. Absorption coefficient is as follows:

$$\alpha = \alpha' + \alpha'' I_{2\omega} \quad (20)$$

We have conducted the numerical solution in equations (8), (9), (19), and (20) and the results of calculations are in quite good agreement with the known experimental results<sup>43</sup> at the following parameters:<sup>38</sup>



$$L_w = 70 \text{ cm}, \alpha' = 10^{-3} \text{ cm}^{-1}, \alpha'' = 10^{-10} \text{ cm/W}, \beta = 3 \cdot 10^{-26} \text{ A m/V}^3, \\ \sigma'_\omega = 4 \cdot 10^{-32} \text{ cm}^3 / (\Omega \cdot W^2) \quad (\sigma''_\omega \gg \sigma'_\omega / I_\omega + \sigma'_\omega / I_\omega), \\ \sigma''_{2\omega} = 2 \cdot 10^{-21} \text{ cm} / (\Omega \cdot W), \quad \sigma''_{2\omega} = 3 \cdot 10^{-26} \text{ cm}^3 / (\Omega \cdot W^2).$$

The calculations have shown (Fig. 7), that the start of visible increase of the second harmonic (offset) shifts to the beginning of fiber with the seeding radiation power increase, and the power of this dependence decreases, as observed in the experiment.<sup>43</sup>

The calculated dependence of the second harmonic power on preparation time (till 1 hour) at different fiber lengths is shown in Fig. 8. We considered that preparation time is connected with net time of influence of pulse radiation consisting of burst of  $N=23$  pulses with duration of  $\tau_p=150\text{ps}$  and pulse repetition rate  $f=1.2 \text{ kHz}$  by the relation:  $t' = t/N\tau_p$ ,  $f \cong 2.5 \cdot 10^5 t$ . Characteristic properties, which were earlier noted in the experiment,<sup>43</sup> have been observed. The first property: the shorter the fiber is, the sooner the second harmonic light saturates, and the second one: the initial growth rate is independent of the fiber length. The calculated dependences of second harmonic power on preparation time (long period of time) for different green seed powers are shown in Fig. 9a and 9b.

The calculations have shown, that maximum of grating amplitude shifts from the beginning of the fiber, and the rate of movement decreases with the increase of time (Fig. 10). From our point of view, such behavior of the grating can be connected with the observed "freezing" of length dependence of the second harmonic power.<sup>43</sup>

The dependencies of the grating phase  $\Phi$  and difference between phases  $\Phi - \varphi$  on the distance along the fiber at different moments of time are shown in Fig. 11. Therefore, the period of the grating changes both on fiber length and in time.

## 5. PHOTOINDUCED SECOND HARMONIC GENERATION IN GAMMA RAY IRRADIATED OPTICAL FIBERS

As it was mentioned above the considered photovoltaic effect and the related changes of  $\chi^{(2)}$  in media with inversion symmetry are analogous in to the bulk photovoltaic effect and the related change of the refractive index  $\Delta n$  in media without inversion symmetry. As know,<sup>44</sup> the latter increases in crystalline quartz after gamma ray irradiation. Therefore it is interesting to investigate the influence of gamma irradiation on photoinduced SHG.

Several fibers (single mode at 1064 nm, core diameter  $8\mu\text{m}$ ) with various compositions as shown in Table I, have been investigated.<sup>28,29</sup> The fiber from naturally occurring quartz with losses of about 80 dB/km at 1064nm had a complex composition with a large number of dopants including OH -  $3.8 \cdot 10^{-2}$  mol%, Na -  $2 \cdot 10^{-3}$  mol%, Fe -  $3 \cdot 10^{-5}$  mol%. Fibers were irradiated using  $^{60}\text{Co}$  source with a dose of  $10^6$  rad at the rate of 400 rad/sec. During the preparation stage, both the pump light from a Q-switched Nd:YAG laser ( $\lambda = 1064\text{nm}$ ) with a pulse length or 50ns and 10Hz repetition rate, and the second harmonic seed ( $\lambda=532\text{nm}$ ), obtained from LiNbO<sub>3</sub> frequency doubler, were simultaneously launched into a 10cm length of fiber. The pump power in the fiber was approximately 1kW, and that of the seed approximately 300W. The preparation process lasted for approximately 1 hour. At low levels of the seed power ( $\approx 30\text{W}$ ) the irradiated fibers exhibited high losses ( $10^3 - 10^4\text{dB/km}$ ). These dropped

irreversible (to  $\approx 100$  dB/km) after the launching of an intense seed ( $\approx 300$ W) indicating that bleaching had occurred. The characteristic bleaching times were measured to be approximately one hour for the fiber made from naturally occurring quartz and approximately 30 sec for germanium doped fiber fabricated from manmade silica.

Table I Comparison of SHG efficiency in gamma-irradiated and nonirradiated fibers.

| Fiber core<br>(cladding: F+P) | SHG efficiency, % |                   |
|-------------------------------|-------------------|-------------------|
|                               | nonirrad.         | irrad.(1Mrad)     |
| natur. SiO <sub>2</sub>       | $10^{-4}$         | $2 \cdot 10^{-4}$ |
| Ge+Ce (0.01mol%)              | $4 \cdot 10^{-4}$ | $9 \cdot 10^{-3}$ |
| Ge                            | $10^{-3}$         | $2 \cdot 10^{-2}$ |

Only the pump power was launched during the measurements, with the second harmonic radiation being observed at the fiber output end. It was found that the efficiency of conversion of pump light into the second harmonic was significantly higher for fibers irradiated with gamma rays.<sup>28,29</sup> The greatest increase in efficiency (by a factor of twenty) was observed in germanium doped fibers as shown in Table I.

It was also discovered that in the case of cerium doping the delay between gamma irradiation and the preparation of fibers had an effect on the conversion efficiency, with the lowest efficiency being observed for the longest time delay (Fig. 12).

We can explain the increased SHG efficiency on the basis of the coherent photovoltaic model of SHG.<sup>6,7</sup> As known,<sup>45</sup> gamma irradiation of quartz fibers leads to a significant increase of color centers concentration. This, in turn, will result in a change of the magnitudes  $\beta$  and  $\sigma$  (probably in an increase). In this way, the relationship of  $\chi^{(2)}$  and the concentration of the photovoltaic centers is probably not directly proportional. It should also be noted that the experimental results shown on Fig. 12 indicate the existence of the decay of the gamma ray induced centers. However, quantitative evaluation of the dependence of the photoinduced second order susceptibility  $\chi^{(2)}$  on the concentration of photovoltaic centers (color centers) requires a detailed microscopic analysis of the above model.

## 6. CONCLUSION

In conclusion the formal analogy between photoinduced SHG in optical fibers and photoinduced light polarization conversion in lithium niobate optical waveguides is evident. Energy exchange between waves with different frequency takes place in the first case while that between waves with different polarization - in the other one. In the case of photoinduced SHG the grating of second order susceptibility is writing as a result of "interference" between waves with different frequency while in the case of photoinduced light polarization conversion the refractive index grating is writing as a result of "interference" between waves with different polarization.

The latter is explained by photovoltaic model based on bulk photovoltaic effect - asymmetry of photoionization in medium without symmetry center. For explanation of photoinduced SHG the idea of existence of coherent photovoltaic effect due to photoionization - asymmetry of photoionization by pump and second harmonic has been proposed.<sup>6</sup> Photovoltaic model of photoinduced SHG on the base

of this idea has been proposed.<sup>7</sup>

The appearance of second-order susceptibility in glass fibers due to photocurrent, arising as a result of interference between two-photon pump ionization and one-photon second harmonic ionization has been suggested.<sup>28,29</sup> Photovoltaic mechanism of second-order susceptibility grating appearance in silica fibers serves to explain a high enough amplitude of the grating as well as the phase matching of second harmonic generation.

Essential increase of conversion efficiency in gamma-ray irradiated optical fibers gives an additional evidence for photovoltaic model of SHG.<sup>28,29</sup>

It has been shown that photoinduced second harmonic amplification is possible at the existence of phase shift between the grating and "interference" pattern ( $E_0^2(\omega)E(2\omega)\exp(-i\Delta kz) + \text{c.c.}$ ).<sup>37,38</sup> The mechanism of appearance of such a shift based on inertial erasure of  $\chi^{(2)}$  grating, being recorded by coherent photocurrent, was suggested.<sup>37</sup> The existence of the threshold pump intensity was explained.<sup>37</sup> The dependencies of second harmonic power and  $\chi^{(2)}$  grating amplitude and phase on distance along the fiber and time from the beginning of the fiber preparation have been calculated.<sup>38</sup> The results of numerical simulation allow to explain known experimental results.

In the case of confirmation of photovoltaic model of photoinduced SHG, the analogy between photoinduced SHG and photoinduced light polarization conversion will be more profound.

## 7. REFERENCES

1. U. Osterberg and W. Margulis, "Dye laser pumped by Nd:YAG laser pulses frequency doubled in a glass optical fiber", *Opt. Lett.*, vol. 11, pp. 516-518, 1986.
2. R.H. Stolen and H.W.K. Tom, "Self-organized phase-matched harmonic generation in optical fibers", *Opt. Lett.*, vol. 12, pp. 585-587, 1987.
3. M.C. Farries, P. St. J. Russell, M.E. Fermann and D.N. Payne, "Second-harmonic generation in an optical fiber by self-written  $\chi^{(2)}$  gratings", *Elect. Lett.*, vol. 23, pp. 322-324, 1987.
4. N.B. Baranova and B. Ya. Zel'dovich, "Extension of holography to multifrequency fields", *JETP Lett.*, vol. 45, pp. 717-720, 1987.
5. F. Ouellette, K.O. Hill and D.C. Johnson, "Light-induced erasure of self-organized  $\chi^{(2)}$  gratings in optical fibers", *Opt. Lett.*, vol. 13, pp. 515-517, 1988.
6. E.M. Dianov, P.G. Kazansky and D. Yu. Stepanov, "On the problem of photoinduced second-harmonic generation in optical fibers", *Sov. J. Quantum Electron.*, vol. 19, pp. 575-576, 1989.
7. E.M. Dianov, P.G. Kazansky, D. Yu. Stepanov and V.B. Sulimov, "Photovoltaic mechanism of photoinduced second-harmonic generation in optical fibers", in *Tech. Digest of Topical Meeting on Integrated Photonics Research*, OSA, Washington D.C., paper MJ1, 1990.
8. N.M. Lawandy, "Light induced transport and delocalization in transparent amorphous systems", *Opt. Commun.*, vol. 74, pp. 180-184, 1989.
9. E.M. Dianov, A.M. Prokhorov, V.O. Sokolov and V.B. Sulimov, "On the theory of photoinduced second-harmonic generation in optical fibers", *JETP Lett.*, vol. 50, pp. 13-14, 1989.

10. B. Lesche, "Microscopic model of second-harmonic generation in glass fibers", J. Opt. Soc. Am. B, vol. 7, pp. 53-56, 1989.
11. V. Mizrahi, Y. Hibino and G.I. Stegeman, "Polarization study of photoinduced second-harmonic generation in glass optical fibers", Opt. Commun., vol. 78, pp. 283-287, 1990.
12. A. Kamal, M.L. Stock, A. Szpak, C.H. Thomas, D.A. Weinberger, M. Frankel, J. Nees, K. Ozaki and J.A. Valdmanis, "Electro-optic sampling measurement of the built in field in fibers conditioned for second harmonic generation", in Tech Digest of OSA Annual Meeting, OSA, Washington D.C., paper PD 25, Nov. 1990.
13. J.K. Lucek, R. Kashyap, S.T. Davey and D.L. Williams, "Second-harmonic generation in glass fibers", J. Mod. Opt., vol. 37, pp. 533-543, 1990.
14. E.M. Zolotov, P.G. Kazansky and V.A. Chernykh, "Photoinduced conversion of polarization in Ti:LiNbO<sub>3</sub> channel waveguides", Sov. Tech. Phys. Lett., vol. 7, pp. 397-399, 1981.
15. A.H. Haus, E.P. Ippen, C. Gabriel, A. Lattes and F.J. Leonberger, "Doubly degenerate four-wave mixing in LiNbO<sub>3</sub> waveguides", Appl. Phys. B, vol. 29, p. 161, 1982.
16. P.G. Kazansky, "Photoinduced conversion of radiation polarization in integrated optics components based on LiNbO<sub>3</sub>", IEEE J. Quantum Electron., vol. 25, pp. 736-741, 1989.
17. D.W. Wilson, E.N. Glytsis, N.F. Hartman and T.K. Gaylord, "Bulk photovoltaic tensor and polarization conversion in LiNbO<sub>3</sub>", in Tech. Digest of OSA Annual Meeting, OSA, Washington, D.C., paper TuD8, Nov. 1990.
18. V.I. Belinicher, "Space-oscillating photocurrent in crystals without symmetry center", Phys. Lett., vol. 66A, pp. 213-214, 1978.
19. E.L. Ivchenko and G.E. Pikus, "New photovoltaic effect in gyrotropic crystals:", JETP Lett. (in Russian), vol. 27, pp. 640-643, 1978.
20. V.M. Asnin, A.A. Bakun, A.M. Danishevsky, E.L. Ivchenko, G.E. Pikus and A.A. Rogachev, "Observation of photoemf dependent on sign of circular polarization of light", JETP Lett. (in Russian), vol. 28, pp. 80-84, 1978.
21. A.M. Glass, D. Von der Linde and T.J. Negrain, "High-voltage bulk photorefractive effect and the photorefractive process in LiNbO<sub>3</sub>", Appl. Phys. Lett., vol. 25, pp. 233-236, 1974.
22. V.I. Belinicher and B.I. Sturman, "Photogalvanic effect in crystals without symmetry center." Sov. Phys. Uspekhi. vol. 23, pp. 199-220, 1980.
23. S.G. Odulov, "Observation of space-oscillating photogalvanic current in ferrum doped lithium niobate crystals", JETP Lett., vol. 35, pp. 10-12, 1982.
24. P.G. Kazansky, A.M. Prokhorov and V.A. Chernykh, "Direct observation of a circular photocurrent in lithium niobate", JETP Lett., vol. 41, pp. 451-454, 1985.
25. M.V. Entin, "Theory of coherent photogalvanic effect", Sov. Phys. Tech. Semicon (in Russian), vol. 23, pp. 1066-1069, 1989.
26. E.M. Baskin and M.V. Entin, "Coherent photogalvanic effect stipulated by quantum corrections", JETP Lett. (in Russian), vol. 48, pp. 554-556, 1988.
27. G.M. Shmelev, Nguen Hong Shon and G.I. Tsurkan, "Photostimulated even acoustoelectric effect", Izv. Vuzov, Fizika (in Russian), vol. 28, pp. 84-88, 1985.
28. E.V. Anoikin, E.M. Dianov, P.G. Kazansky and D. Yu. Stepanov, "Photoinduced second-harmonic generation in gamma-ray-irradiated optical fibers", Opt. Lett. vol. 15, pp. 834-835, 1990.
29. E.V. Anoikin, E.M. Dianov, P.G. Kazansky, D. Yu. Stepanov, V.O. Sokolov and V.B. Sulimov, "Photoinduced second-harmonic generation in gamma-ray-irradiated optical fibers", Sov. J. Tech. Phys. Lett. (in Russian), vol. 17, pp. 926-929, 1989.
30. D.Z. Anderson, V. Mizrahi and J.E. Sipe, "A model for second-harmonic generation in fibers

based on anisotropic photoexcitation of defect electrons", in Tech. Digest of OSA Annual Meeting, OSA, Washington, D.C., paper PD24, Nov. 1990.

31. N.B. Baranova, B. Ya Zel'dovich, A.N. Chudinov and A.A. Chulginov, "Polar asymmetry of photoionization in field with  $\langle E^3 \rangle \neq 0$ ", Sov. JETP (in Russian), vol. 98, pp. 1857-1869, 1990.

32. C.M. Gee and G.D. Thurmond, "Wideband traveling-wave electro-optic modulator", Proc. SPIE, vol. 477, p. 17, 1984.

33. B.I. Sturman, "Photogalvanic effect - a new mechanism of nonlinear interaction of waves in electro-optics crystals", Sov. J. Quantum Electron., vol. 10, pp. 276-280, 1980.

34. E.M. Zolotov, P.G. Kazansky, A.M. Prokhorov and V.A. Chernykh, "Photovoltaic mechanism of degenerate four-wave mixing in optical Ti:LiNbO<sub>3</sub> waveguides", in Tech. Digest Fourth Int. Conf. Integrated Opt. Opt. Fiber Commun., Tokyo, pp. 435-436, June 1983.

35. I.F. Lam and H.W. Yen, "Dynamics of optical TE to TM mode conversion in LiNbO<sub>3</sub> channel waveguides", Appl. Phys. Lett., vol. 45, pp. 1172-1174, 1984.

36. T.E. Tzai, M.A. Saifi, E.J. Friebele, D.L. Griscom and U. Osterberg, "Correlation of defect centers with second-harmonic generation in Ge-doped and Ge-P-doped silica-core single-mode fibers", Opt. Lett., vol. 14, pp. 1023-1025, 1989.

37. E.M. Dianov, P.G. Kazansky and D. Yu. Stepanov, "A mechanism of arising of the efficient photoinduced SHG in optical fibers", Sov. J. Quantum Electron. (in Russian), vol. 17, pp. 926-927, 1990.

38. E.M. Dianov, P.G. Kazansky and D. Yu. Stepanov, "Simulation of effective second-harmonic generation process in optical fibers", in Tech. Digest of OSA Annual Meeting, OSA, Washington D.C., paper TuU4, 1990.

39. V.L. Vinetsky, N.V. Kuchtarev, S.G. Odulov and M.S. Soskin, "Dynamic selfdiffraction of light beams", Sov. Phys.-Uspekhi (in Russian), vol. 129, pp. 113-137, 1979.

40. W. Margulis, I.C.S. Carvalho and J.P. von der Weid, "Phase measurement in frequency-doubling fibers", Opt. Lett., vol. 14, pp. 700-702, 1989.

41. K. Koch, G.T. Moore, "Two-color interferometry using a detuned frequency doubling crystal" presented at the International Workshop on Photoinduced Self-Organization in Optical Fibers, Quebec City, Canada, May 10-11 1991.

42. E.M. Dianov, P.G. Kazansky, D. Yu. Stepanov, D.S. Starodybov, "Observation of phase mismatching during second-order susceptibility grating preparation process", submitted for CLEO '91, Baltimore, MD.

43. B. Bardorf, C. Krautshick, U. Osterberg, G.I. Stegeman, J.W. Leitch, J.R. Rotge and T.F. Morse, "Study of the length dependence of frequency-doubled light in optical fibers", Opt. Commun., vol. 73 pp. 393-397, 1989.

44. V.M. Fridkin, "Review of recent work on the bulk photovoltaic effect in ferro and piezoelectrics", Ferroelectrics, vol. 53, pp. 169-187, 1984.

45. E.J. Friebele, D.L. Griscom and G.H. Sigel, "Defect center in germanium-doped silica-core optical fibers", J. Appl. Phys., vol. 45, pp. 3424-3428, 1974.

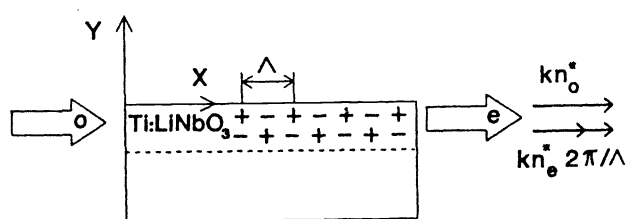


Fig. 1 Photoinduced polarization conversion of waveguide modes

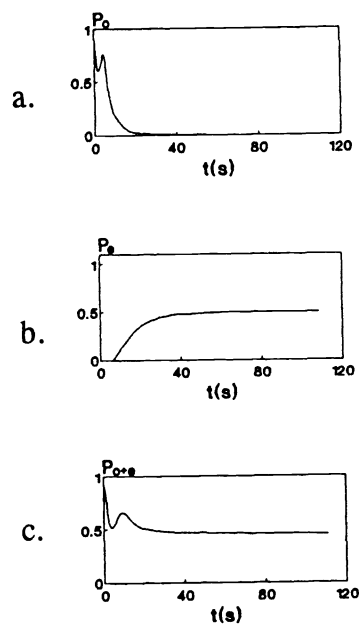


Fig. 2 (a) Time dependence of ordinary, (b) extraordinary, and (c) total wave power.

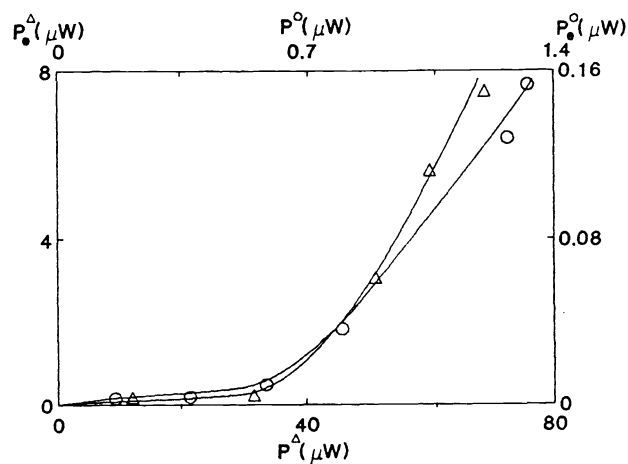


Fig. 3 Extraordinary mode power  $P_e$  as a function of total light power  $P$  in waveguides fabricated in air (o) and humid oxygen ( $\Delta$ ).

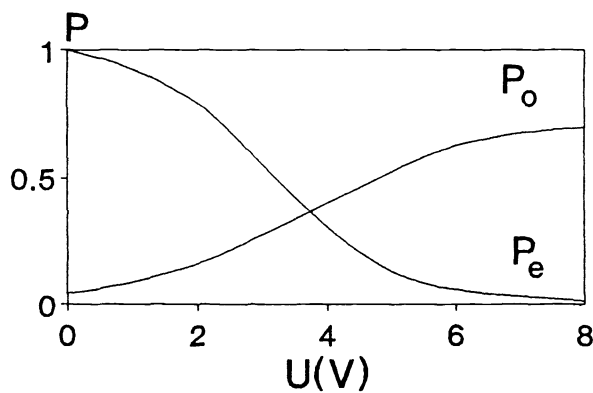


Fig. 4 Voltage dependence of extraordinary  $P_e$  and ordinary  $P_o$  wave powers.

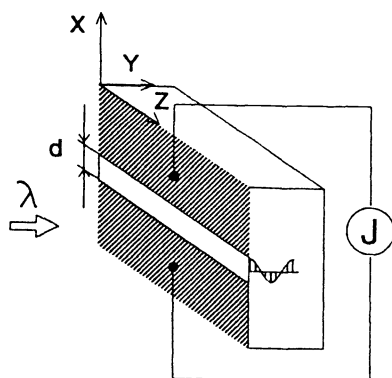


Fig. 5a Arrangement for measuring the spatially oscillating photocurrent.

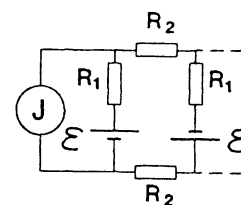


Fig. 5b Equivalent circuit.

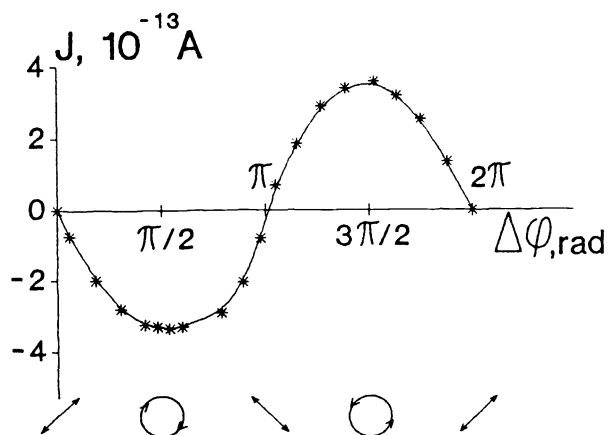


Fig. 6 The current  $I$  versus the phase shift  $\Delta\phi$ .

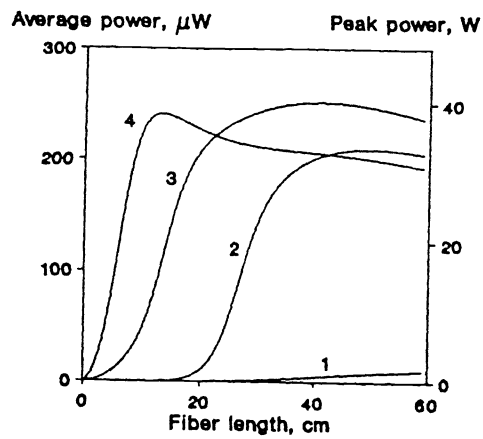


Fig. 7 Length dependences of SH power for various green seed powers. Average green seed power: 1,2 - 0.3nW, 3 - 1μW, 4 - 9.5μW, preparation time: 1,3,4, - 60 min., 2 - 180 min. Average pump power - 150mW.

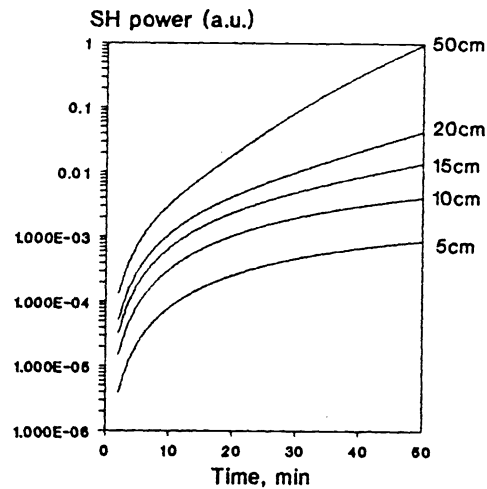


Fig. 8 Time dependences of SH power for various fiber lengths. Average green seed power - 1pW. Average pump power - 150mW.



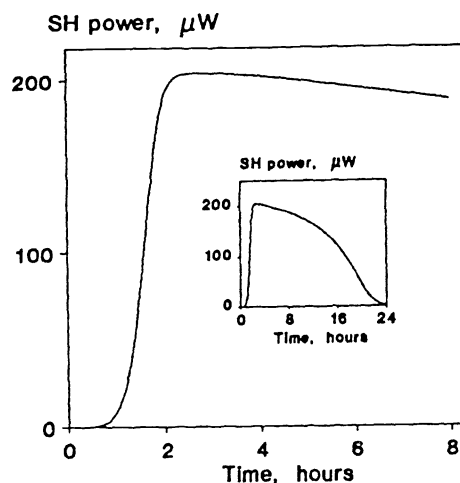


Fig. 9a Time dependences of SH power (long period of time) for various green seed powers.

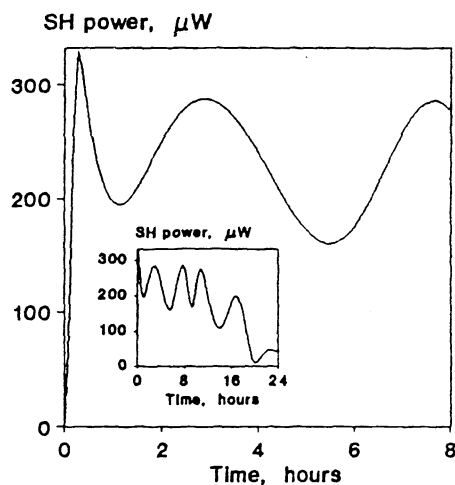


Fig. 9b Average pump power -150mW.  
Average green seed power: a - 0.3nW, b - 9.5μW.

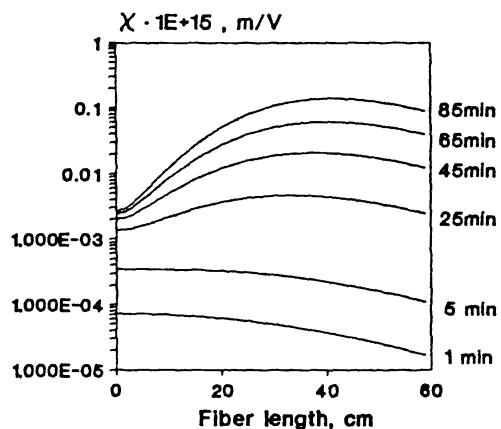


Fig. 10 Length dependences of  $\chi$  for various preparation time.  
Average green seed power 0.3nW. Average pump power - 150mW.

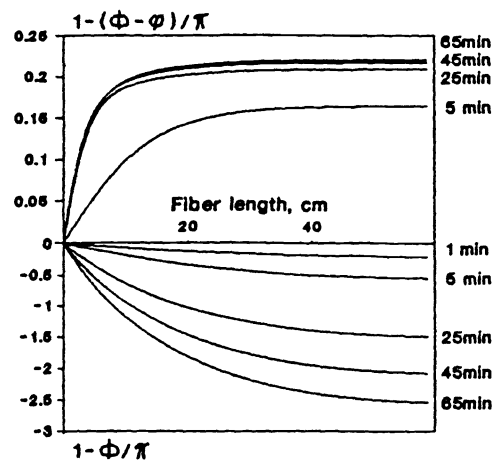


Fig. 11 Length dependences of  $\Phi$  and  $\Phi - \varphi$  for various preparation times. Average green seed power - 0.3nW. Average pump power - 150mW.

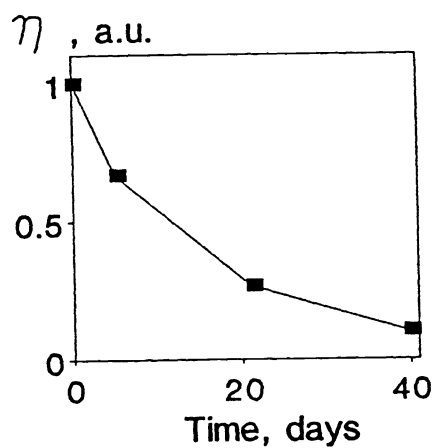


Fig. 12 Time dependence of SHG efficiency.